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SEDIMENT SOUND SPEED MEASUREMENTS 'IN SITU' FROM BATHYSCAPH TRI--ETC(U)

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6 SEDIMENT SOUND SPEED MEASUREMENTS IN SITU FROM BATHYSCAPH TRIESTE.

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SEDIMENT SOUND SPEED MEASUREMENTS *IN SITU* FROM BATHYSCAPH TRIESTE

E. L. Hamilton, Code 3190

ABSTRACT

Use of the bathyscaph TRIESTE has permitted the first deep-water *in situ* measurements of the speed of sound in sea-floor sediments (other than seismic). Measurements were made at 3 stations off San Diego during August-October 1962, in water depths from 338 to 1235 meters, using specially designed probes which measured sound travel time over a 1 meter path 18 inches below the water-sediment interface at frequencies of 25 kc/sec.; probe accuracy was about ±0.5 m/sec. Three additional stations were made with the probes in sand bottoms by scuba diving in shallow water.

Results and conclusions: In correcting laboratory measurements of sound speeds in sediment to *in situ* conditions in the sea floor, full corrections should be made for temperature and pressure, using tables for sound speed in sea water (*e.g.*, Wilson, 1960). Use of present sound speed vs porosity curves for high-porosity sediments off San Diego (Shumway, 1960) allows predictions of *in situ* sound speeds of less than 1% error. Present sound speed vs porosity curves for sands are not considered accurate and a tentative equation is given for sands (pending further study). Sound speeds in sediment 2.3% less than in the water just above the bottom were measured at 3 stations from the TRIESTE. Investigators should quit trying to devise single equations and cures that will fit all types of sediments; probably 5 to 7 curves will be necessary to describe the porosity vs sound speed relationships for common sea-floor sediments.

This memorandum has been prepared because it is believed that the information may be useful in this form to others at NEL and to a few persons or activities outside of NEL, and should be presented in the shortest time possible. This memorandum should not be construed as a report as its only function is to present for the information of others a small part of the work on NEL Problem L4-1; a finished report will be made on this subject after the next series of dives of the TRIESTE (Spring and early Summer 1963).

The writer appreciates the interest and skillful cooperation of LCDR D. L. Keach and LT G. W. Martin who piloted the bathyscaph TRIESTE during the dives noted in this memorandum. Mr. S. H. Abernethy and Mr. J. McQuay helped to keep the equipment going.

SEDIMENT SOUND SPEED MEASUREMENTS MADE *IN SITU* FROM BATHYSCAPH TRIESTE

E. L. Hamilton, Sea Floor Studies (Code 3190)

INTRODUCTION

Use of the bathyscaph TRIESTE, at the Navy Electronics Laboratory, has enabled members of the Sea Floor Studies Project to make several types of *in situ* measurements in sea-floor sediments. Using probes which are inserted into the bottom sediments when the TRIESTE is on or near the sea floor, has allowed, for the first time, sound speed and attenuation measurements *in situ* beyond the range of depths of a free diver. During the July-October 1962 diving series such measurements were made off San Diego in water depths from 338 to 1235 meters (Figure 1).

The objectives of the program were as follows:

(1) To perform, for the first time, deep-water, *in situ* acoustic measurements in sea-floor sediments (other than by seismic methods).

(2) Use of a higher precision measuring device than heretofore used, in order to refine such measurements and allow the study of the smaller variable factors.

(3) To compare *in situ* acoustic measurements with those made in the laboratory to: (a) study techniques of correcting laboratory values to *in situ* values, and (b) to study disturbance to the sediments made in the coring process.

(4) To study techniques of making deep-water *in situ* measurements from a submersible.

In situ measurements prior to the present were made by divers in waters less than 100 feet deep. (Hamilton, *et al.*, 1956). In most cases

the errors inherent in these measurements were larger than the changes of sound speed owing to temperature, pressure, or other small factors. The use of the TRIESTE allowed *in situ* measurements in deep water where such changes become significant.

There have been a number of theoretical and laboratory studies of sound speed made on artificial sediments or models of sedimentary structure, but relatively little work has been done on "undisturbed" samples. This is surprising in view of the importance of the subject to military and basic science. As a matter of fact, there have only been about 440 published measurements made on cores of which 260 were from deep-sea areas, and 180 from continental shelves and slopes. The advent of free-diving techniques (such as with the Aqualung) allowed studies to be conducted on the sea floor to depths of about 150 feet. These diving ventures had two advantages: *in situ* measurements could be made, and diver-taken samples could be returned to the laboratory without being exposed to the air. To date, 41 *in situ* stations have been made, including the presently reported 6 stations (Hamilton, *et al*. 1956). Diver-taken samples have been reported by Hamilton, *et al*. (1956) and Shumway (1956, 1960). Sound-speed measurements on cores have been published by Shumway (1960), Sutton, *et al*, (1957) and Laughton (1957). An excellent recent summary has been published by Nafe and Drake (1961). It would be inappropriate, here, to outline the theoretical, empirical, and statistical work of the above, and other papers, except where it is pertinent to the findings of this progress report.

As previously noted, one of the major purposes of this program was (and will continue to be) to study the corrections to laboratory-determined

velocity and attenuation measurements in order to relate them to valid *in situ* properties. From a laboratory study of pressure and velocity on one sample (Laughton, 1957), and from theoretical considerations, it has been assumed that the pressure correction should be "about the same as for sea water"; namely, a positive increment to be added to the atmospheric determination of the laboratory. From Sutton, *et al.* (1957) and, especially, Shumway (1960), the temperature corrections were known to be "about" the same as for sea water -- an amount to be substracted from the laboratory determination. Shumway (1958, p. 504) summarized all that was known with the statement that, in his five samples, sound velocity changes with temperature at about the same rate as for water alone, which he attributed to the dominant role played by the temperature effect on water compressibility. It has been stated (Sutton, *et al.*, 1957), and is common practice to assume, that the temperature and pressure corrections cancel each other and that the laboratory determination will be within 1% of the supposed *in situ* determination and corrections need not be made; this is only true under certain given conditions, as will be further discussed.

Good attenuation measurements were too few to discuss in this progress report; they will be included in a final report.

EQUIPMENT AND METHODS

In situ measurements were made by using a velocity-attenuation meter produced for the Navy Electronics Laboratory by Scientific Service Laboratories, Dallas, Texas (Shumway and Huckabay, 1961). Briefly, the equipment consists of three probes, each 1-1/4 inches in diameter, fastened to a

rigid beam in such a manner that when the beam is on the sediment surface, the probes are inserted a variable, pre-set depth into the sediment. In the presently reported tests the transducers were 18 inches into the sea floor. A pulse-actuated magnetostrictive transducer is used as a sound source and barium titanate cylinders as receivers. The velocity is determined by measuring, with a decade counter, the travel time between receivers 1 and 2 which are 1 meter apart; frequenc~~ies used were between 25 and 30 kc/sec.~~y normally used was 25. c/sec. Absorption measurements were made by matching superimposed oscilloscope traces of the signals from the near and far receivers. These probes were attached to the bathyscaph TRIESTE in such a manner that when the TRIESTE was on or near the bottom the probes were inserted by gravity into the sediment (Fig. 2).

The true path length between the receiving probes was determined by measuring the travel time of sound between the receivers, in sea water of known sound speed. The speed of sound in the sea water was known by using its temperature, pressure, and salinity, to enter Wilson's (1960) tables and by simultaneous use of a velocimeter developed by the Lockheed Missiles and Space Company. ~~(Suellentrop, et al, 1961).~~ Calibration indicated that the accuracy of the probes was approximately ± 0.5 m/sec.

One subject frequently mentioned in discussions of sea-floor in situ measurements is: "what amount of weight is necessary to drive a certain diameter of probe into the sediment?". This, of course, depends on the shear strength of the sediment, friction parameters of the probe (pile)-sediment, velocity of probe entrance, etc. On the first dive with the sound-velocity probes in the TRIESTE it was determined that the probes did not go all the way (18 inches) into the soft sediment as the TRIESTE settled

to the sea floor. It was, however, quickly determined that the TRIESTE pilot could swing the vessel in back-and-forth motions so that the probes could be "wiggled" into the sea floor to full penetration. This is important in that such maneuvering will permit the use of much larger diameter probes, and with reasonable weights, in all categories of desired measurements, including sound speed and attenuation. Use of larger diameter probes in sound-speed studies will permit measurements at lower frequencies which is highly desirable.

Small (2-1/2" diam.) corers were attached to each end of the probe frame so that sediment cores were taken close to the area of velocity-attenuation measurements. Recorders within the bathyscaph sphere recorded the water temperatures and depths; salinity samples of the bottom water were taken when desired. From within the sphere, the observer could see and photograph the sea floor, and ascertain the attitude and penetration of the probes into the sediment.

In the laboratory, the sediments were analyzed using standard methods; the following determinations were made: median grain size, density, porosity, and percentages of sand, silt, and clay. The velocity of sound in the cored sediment was measured by a pulse technique (Shumway and Abernethy, 1962). The salinity of the bottom water was determined by titration. It should be emphasized that the sediments discussed here are of the upper 18 inches of the sea floor.

RESULTS

Three dives in the bathyscaph TRIESTE in water depths from 338 to

1235 meters yielded *in situ* velocity measurements (Stas. 4, 5, 6); diving from small boats in connection with the same velocity-attenuation probes gave three measurements in near-shore sandy environments (Stas. 1, 2, 3). In order to employ a full depth range of laboratory and *in situ* determinations (as available to the writer), laboratory determinations of velocity made on a red-clay core from the sea floor at the Mohole site (near Guadalupe Island in 3558 meters of water) were compared to the *in situ* values derived by Fry and Raitt (1961) using seismic reflection techniques (Sta. 7). Thus, for purposes of this paper, we have available a range of sediments from water depths of 8 to 3558 meters for which we have *in situ* and laboratory measurements of sound speed. Information and tests on these sediments are shown in Tables 1, 2 and 3. Attenuation will be discussed in a final report (after more tests have been made).

DISCUSSION AND CONCLUSIONS

Although attempts have been made to derive theoretical equations for sound speed in sea-floor sediments, none of them are usable for practical purposes because of difficulties which are discussed at length by Hamilton, (1956); Hamilton, *et al*, (1956); Sutton, *et al*. (1957); Laughton, (1957) and Shumway, (1960). As a consequence, these previous investigators have derived empirical formulas, equations, and curves relating the various physical properties of sediments to sound speed. Porosity has been the most usable property directly related to sound speed and, given porosity, it has been considered practical and accurate to predict sound speeds and attenuations *in situ*. Pressure and temperature corrections may or may not be made according to the philosophy of the estimator, and one has a variety of curves and equations to choose from (among the various papers previously

cited). One of the main difficulties with most of these curves and equations is that they attempt to show inter-relationships between properties in all types of sediments from all depths and environments; although it must be pointed out that all of these investigators understand and usually point out that there is no universally accurate equation.

An understanding of the structure of various sediments indicates that there will never be a universally valid sound-speed equation for all sediment types. The two most common structures in sediments are the grain-to-grain contacts of the sands, and the "card house" structure of the finer silts, clays, and mixtures of the two (Rosenqvist, 1960). The clays have adsorbed water films around the fine particles, and it is doubtful if the mineral grains, in a strict sense, touch at all (Lambe, 1961; Rosenqvist, 1960). Such particles apparently move within the sound field, and also act as sound scatterers (Urick, 1947; Urick and Ament, 1949; Ament, 1953). In a separate paper (Hamilton and Moore, in preparation), the view is expressed that it is probably the inter-particle forces (such as van der Waals and Coulombic forces) which hold and yield to the elastic wave. If so, then, investigators must delve into the clay and finer-particle mineralogy, and depositional history of the sediments, in order to refine the presently understood acoustic properties of sea-floor sediments.

The sands, on the other hand, have less porosity (less water) and definite grain-to-grain contacts which transmit the elastic sound pulses through the solids of the sediment structure. As a consequence, sound speed is always higher in sands than in clays.

The conclusion, then, is that investigators should, at this time,

stop trying to derive equations which will apply to all sediments, and should break the investigations up according to the factors of sediment structure involving sound speed (i.e.: structural type, mineralogy, strength, etc.). At this time the following breakdown of the main types appears reasonable (using nomenclature of Shepard, 1954):

A. Continental and island shelves and slopes.

1. Sands (median grain diameter greater than 0.062 mm)

a. Quartz sands.

b. Calcareous sands.

c. Volcanic sands.

2. Sandy coarse silts and silty sands (may belong in (1) above.

3. Fine silts and clays, and mixtures of the two.

B. Deep sea.

1. Clay, silty clay, and clayey silt (sediments with less than about 30% Calcium Carbonate).

2. Calcareous oozes.

Sutton, et al. (1957) have shown that calcareous oozes have a greater sound speed for a given porosity than do non-calcareous clays. These investigators estimate the effect (additive) to be (0.00135 km/sec.)(%$CaCO_3$). The percentages of $CaCO_3$ in their samples clusters around 29% ± 5% and 94% ± 5% with few samples between. It would appear, from these data, that the traditional dividing line between deep-sea clay and calcareous ooze (30% $CaCO_3$) may be of consequence, also, in sound speed studies, but this matter needs more investigation. A foraminiferal "ooze" (the most common variety of calcareous ooze) is really a special type of sand or sandy silt, with "grains" of hollow, filled, or partially filled, calcium

carbonate. It may be that many of these sediments belong in a special calcareous-sand, sound speed curve, and should not be included in curves and equations concerned with deep-sea, clay-structure sediments.

There is not yet enough data to produce the family of curves called for by the above distinctions. Most of the sediments used by Shumway (1960 p. 661) to derive his curve were from the continental shelf off the West Coast, although he had other sediments from the Arctic and deep-sea. At this time, Shumway's curve appears to allow reasonable prediction of in situ sound speeds for the fine-grained sediments on the continental shelf and slope off the West Coast (and, probably, for similar sediment types in similar environments elsewhere). Pending further study it should also be used for Pacific deep-sea clays. This curve, however, needs correction for the sands, as discussed below.

LOW-VELOCITY PHENOMENON

The fact has been well established that many high-porosity, fine-grained sediments have sound velocities less than in the sea water just above the bottom: in the laboratory by Hamilton, et al, (1956); Sutton, et al, (1957); Laughton, (1957); Shumway, (1960), and in situ by seismic studies and by actual measurements at the Navy Electronics Laboratory by diving (Hamilton, 1956) and the presently reported work from the TRIESTE. Table 3 illustrates this phenomenon in the latter four samples; at all three TRIESTE in situ locations the speed of sound is 2.3% less than in the bottom water; at the Mohole Site: 2.4% less. These in situ measurements thus, again, confirm the fact that the high-porosity (greater than about 60%) sediments have sound speeds less than in the water just above the bottom.

LABORATORY TO *IN SITU* SOUND SPEED CORRECTIONS

In view of the previous work and opinions regarding laboratory vs *in situ* sound speeds, the first study of corrections involved the application of the same corrections to the sediments that one would make for sea water alone. This approach proved to be correct. The actually measured *in situ* values were very closely approached by application (to laboratory values) of temperature and pressure corrections derived from tabled of the speed of sound in sea water. However, the opinion that such corrections cancel out and need not be applied is *not* well founded, especially for sediments of the continental shelves and slopes, or when accurate *in situ* estimates of sound speed in deep-sea sediments ~~be~~ are justified by accurate laboratory measurements, and knowledge of the *in situ* properties of the bottom water.

For many years sound speeds in sea water were determined from Kuwahara's, ~~or~~ Matthews', or other tables. Recent work by Del Grosso (1952) and Wilson (1960) have shown that Kuwahara and Matthews were incorrect by about 3 m/sec. at atmospheric pressure (Wilson substantiated Del Grosso) Wilson (1960a, 1960b, 1962) has derived the equations and published tables which are now being used at NEL for the speed of sound in sea water. (An interesting aspect of this subject is Mackenzie's work (1961) using the TRIESTE to determine correct deep-water sound speeds.) Wilson's tables are entered through pressure rather than depth. For this purpose he has pressure-depth tables for various salinities and temperatures (Wilson, 1959). The temperature and pressure corrections applied to the sediment sound speeds of this report are derived directly from Wilson (1960a). As noted above, temperature and pressure corrections do not always cancel out and

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should be made to laboratory determinations, as a study of Table 4 will ~~will~~ show. If one has a measuring device which determines sound speed within less than 1 m/sec. (or even 10 to 15 m/sec.: Shumway, 1960; Sutton, et al, 1957), then each correction should be separately made. Table 4 indicates that the combined corrections for temperature and pressure vary (in the realistic hypothetical situation shown) from 9 m/sec at a depth of 100 meters to about 45 meters per second (the maximum) around 1000 meters depth; this amounts to a maximum of 3%. Careful note should also be made of the laboratory temperature of the sediment at the time of any sound-velocity measurements. Wilson's tables indicate that variations in "room temperature" (say 70°F to 85°F) might cause sound speed variations of as much as 20 m/sec.

If one were given the sediment cores taken by the TRIESTE and asked to predict the sound speed, in situ, in the sediments, the correct procedure would be to first determine the porosity of the sediment. Then enter the curve of Figure 3 (from Shumway, 1960, p. 661) and pick off the sound speed corresponding to the porosity. Shumway's curve was an empirical best fit for determinations made in the laboratory at an average temperature of 22.8°C. The next step is to enter Wilson's tables for Sound Speed in Sea Water and make the appropriate corrections from one atmosphere pressure and 22.8°C to the temperature and pressure in situ as one would do for sea water. One would then apply these corrections to the value taken from the porosity-sound speed curve. This procedure was followed with the presently reported samples and results are indicated in Table 2 and Figure 3, both for values taken from the curve and corrected, as above, and actual in situ measurements taken from the TRIESTE. For the three fine-grained sediments, the errors of the

predictions would have been 13, 0, and 2m/sec.; the average error for the three stations being 5 m/sec. or about 0.3%.

Sample No. 7 is from a red-clay core from the sea floor at the Mohole Drilling Site off Guadalupe Island in 3558 meters of water. Using the laboratory-determined porosity to enter the porosity-velocity curve (Figure 3), and then applying the temperature and pressure corrections from Wilson's Tables yields an estimated *in situ* value for sound speed of 1477 m/sec. Fry and Raitt, (1961), using a reflection technique, have reported an *in situ* value of 1481 m/sec., a difference from the estimate of 4 m/sec. which is consistent with the differences noted from the TRIESTE observations.

Sound ~~speeds~~ velocities determined with the TRIESTE velocity-attenuation probes in near-shore sandy bottoms by diving from a small boat show significant differences from Shumway's curve. The writer has corrected all of Shumway's values of sound speed for sand to a common temperature (22.8°C: Shumway's average) and has plotted them together with Shumway's curve (Figure 4). As can be readily seen, the curve does not describe the porosity-velocity relationship properly; the curve is too far to the right, or in the direction of lower porosities. When the *in situ* measurements of the present study are plotted on the figure, they too, fall to the left of the curve. In other words, the curve of Shumway's Equation 7 (Shumway, 1960, p. 661) adequately shows porosity-sound-speed relationships in the high porosity, fine-grained sediments studied so far, but does not properly define the porosity-sound-speed relationship of sands (at least the sands off San Diego).

It appears that a new relationship should be derived for these near-shore sands.

The present measuring capabilities of the TRIESTE sound velocity probes will permit accurate *in situ* measurements in the near-shore sands and will permit the establishment of a more accurate relationship between sound speed and porosity than heretofore derived. Almost all natural sands fall within the porosity range of 35% to 50%. Within this porosity range theoretical and empirical studies indicate an almost linear relationship between sound speed and porosity. Computing a linear least-squares line for sands, using the best data available from Shumway's work, plus the three stations established with the TRIESTE probes, indicates the following relationship:

> Sound speed, Km/sec. @22.8°C = 2.362 - 1.568n,
>
> where "n" is the porosity of the sediment expressed as a fraction of the total volume. This line is plotted in Figure 4.

It is suggested that the above equation be used for estimating sound speeds in sea-floor surficial quartz sands which are loose aggregates (*i.e.*: exhibit no cementation between the grains). Further careful measurements *in situ* from the TRIESTE and from small boats, and in the laboratory, will be necessary before a better relationship can be established which will involve the dynamic rigidity, compressibility, and density of the sands.

Work planned for the next two diving series of the TRIESTE in the Spring and Summer of 1963 should allow the presentation of revised sound speed-porosity curves for high-porosity continental shelf and deep-sea sediments, as well as for near-shore sands; pending such revisions it is suggested that Shumway's curve be used for Pacific sediments with porosities

greater than 50%, but that the empirical relationship shown above be used for near-shore quartz sands. These curves (Figures 3 and 4) are plotted with data for a common temperature of 22.8°C and 1 atmosphere of pressure; full, and separate, corrections for temperature and pressure should be made for *in situ* conditions using Wilson's Tables for Sound Speed in Sea Water (1960a).

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TABLE 1. Properties of sediments

Sta. (i)	Water Depth (m)	Sediment Type	Med Gr. Diam. (mm)	Density (gr/cc)	Porosity (%)	Sand (%)	Silt (%)	Clay (%)
1	8	Fine Sand	0.23	1.99	43.7	100.0		
2	9	Fine Sand	0.18	1.97	43.6	100.0		
3	11	Med. Sand	0.26	1.96	44.6	100.0		
4	338	Sandy silt	0.05	1.65	65.0	29.0	55.8	15.2
5	951	Clay. silt	0.009	1.38	86.7	2.7	63.6	33.7
6	1235	Clay. silt	0.008	1.34	85.5	2.5	63.0	34.5
7	3558	Silty clay	0.003	1.51	80.9	0.0	44.3	55.7

Notes:

(i) All off San Diego (see Figure 1) except No. 7 (at Mohole Guadalupe Site: Lat. 28° 59' N., Long. 117° 30' W.). Sta. 4 is TRIESTE Dive No. 106, Sta. 5=Dive 112, Sta. 6=Dive 109.

TABLE 2. Sound speeds in sediment (m/sec).

Sta.	Laboratory (1)	In situ: Corrected Lab. (2)	In situ: Measured (3)	In situ minus corr. lab.
1	1647	1636	1673.0[a]	37
2	1649	1619	1639.8[a]	21
3	1633	1613	1621.1[a]	8
4	1509	1473	1459.7[b]	-13
5	1495	1449	1449.4[b]	0
6	1494	1449	1450.7[b]	2
7	1490	1477	1481[c]	4

Notes:

(1) Using measured porosity to enter sound speed curve of Shumway "Equation 7" (1960, p. 661); also Figure 3, this paper.

(2) Laboratory values from curve (see Note 1), corrected for temperature and pressure to in situ conditions (see text).

(3) Sound speed measured in situ:
"a" by free diving using TRIESTE probes.
"b" from bathyscaph TRIESTE.
"c" from seismic reflection (Fry and Raitt, 1961).

TABLE 3. In situ ratios of sound speeds (sediment/bottom water)

Sta.	Sound speed, m/sec. Btm. water	Sediment	Ratio speeds sed./btm. water
1	1503.5	1673.0	1.113
2	1496.0	1639.8	1.096
3	1507.7	1621.1	1.075
4	1494.5	1459.7	0.977
5	1483.1	1449.4	0.977
6	1484.2	1450.7	0.977
7	1517	1481	0.976

TABLE 4. Corrections to sound speeds in sediment and in sea water owing to temperature and pressure (hypothetical case).

Depth (m)	Temp.(1) (°C)	Pressure(2) (Kg/cm²)	Sound Speed Corrections(3), (m/sec.) ΔVt	ΔVp	$\Delta Vstp$	Total	%(4)
0	21.8	1.03					
100	18.7	11.32	-11.09	+ 1.66	-0.01	-9.4	0.6
200	14.3	21.61	-24.48	+ 3.31	-0.04	-21.2	1.4
400	9.0	42.20	-42.85	+ 6.63	-0.07	-36.3	2.4
600	6.4	62.81	-52.81	+ 10.12	-0.09	-42.8	2.9
800	5.1	83.44	-58.04	+ 13.46	-0.10	-44.7	3.0
1000	4.3	104.09	-61.35	+ 16.83	-0.11	-44.6	3.0
1200	3.5	124.75	-64.71	+ 20.19	-0.12	-44.6	3.0
1600	2.6	166.15	-68.58	+ 26.97	-0.12	-41.7	2.8
2000	2.2	207.61	-70.33	+ 33.80	-0.14	-36.7	2.4
3000	1.7	311.60	-72.54	+ 51.09	-0.18	-21.6	1.4
4000	1.5	416.04	-73.43	+ 68.70	-0.24	- 5.0	0.3
6000	1.5	626.26	-73.43	+104.87	-0.44	+31.0	2.1

Notes:

(1) Typical of Pacific Ocean, Lat. 40°N. to 40° S; DeFant, 1961, v. 1, p. 118-153.

(2) Wilson, 1959; Table IX (for S = 35.00ppt, T = 0°C; g = 980.665 cm/sec/sec.).

(3) From Wilson, 1960; assuming salinity of 35.00 ppt and correcting for temperature and pressure shown.

(4) To a sediment sound speed determined at 22.8°C and 1 atmosphere pressure; % correction assuming sediment speed was 1500 m/sec, salinity 35.00ppt.

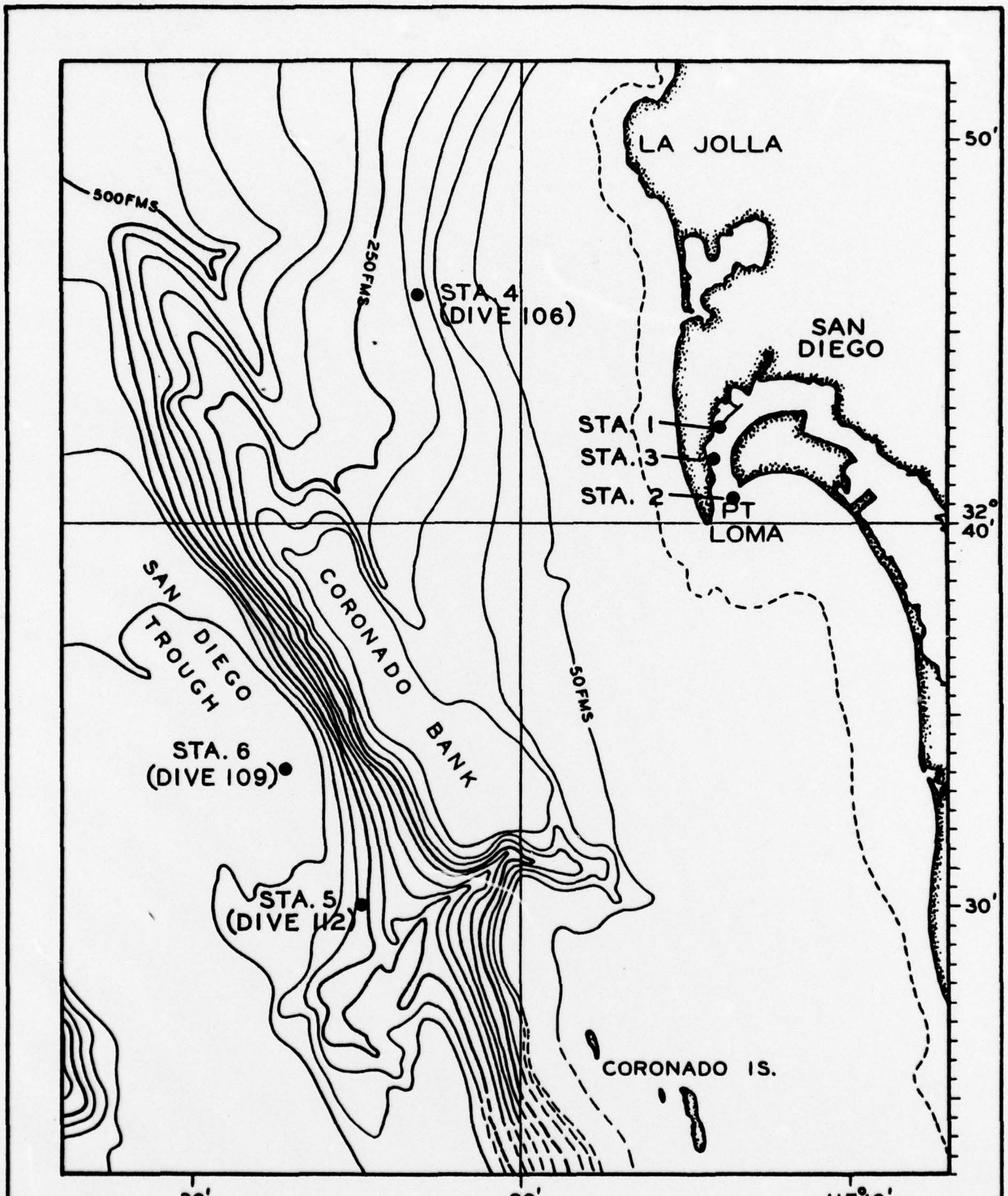

FIGURE 1. LOCATION OF STATIONS OFF SAN DIEGO

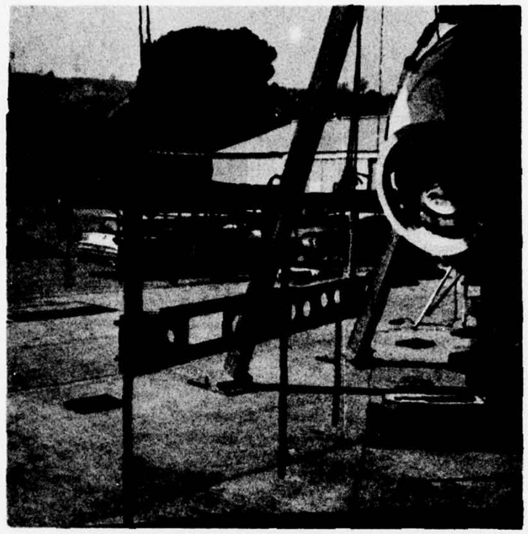

Figure 2. a. Velocity-attenuation probes attached to TRIESTE (sphere with window to right) in "dry dock".

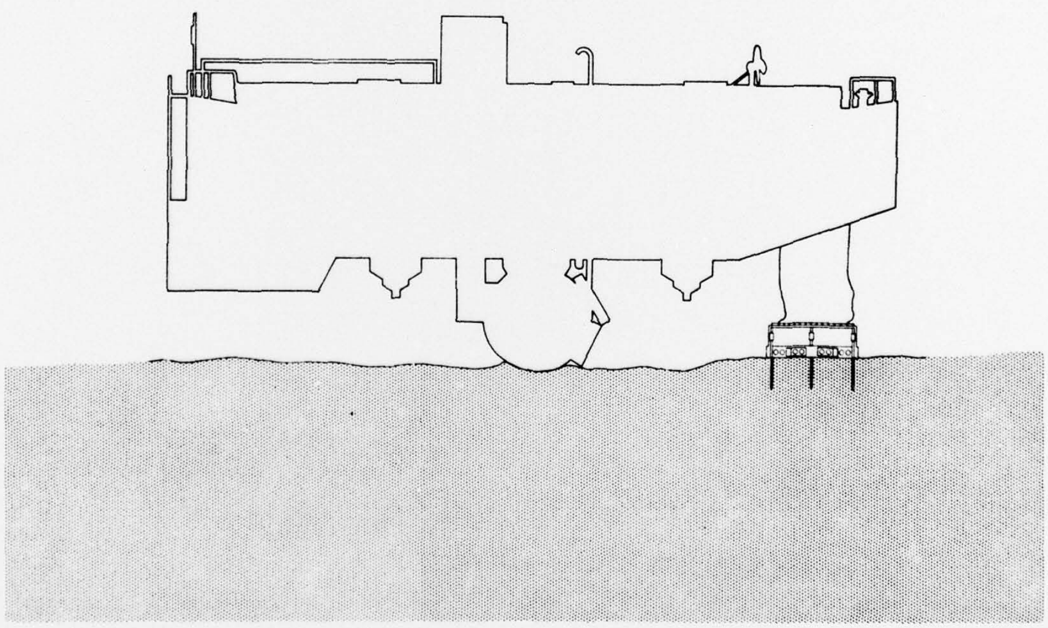

Figure 2. b. Diagram of TRIESTE on the sea floor with probes in the sediment.

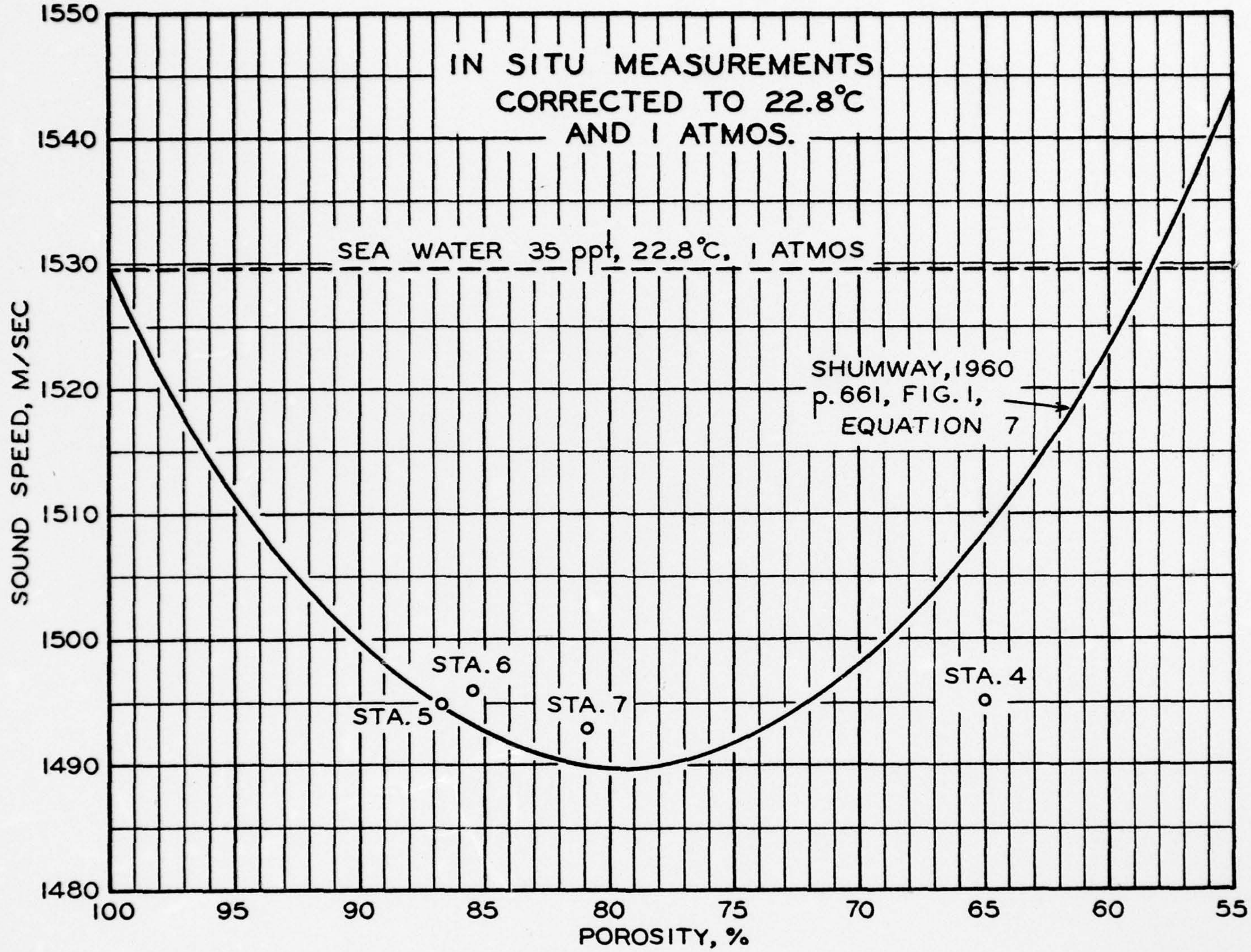

Figure 3. Sound speed vs porosity for fine-grained sediments (Shumway, 1960) compared with *in situ* measurements from the TRIESTE (Stas. 4,5,6) and at the Mohole (Guadalupe) Site (Sta. 7; Fry and Raitt, 1961).

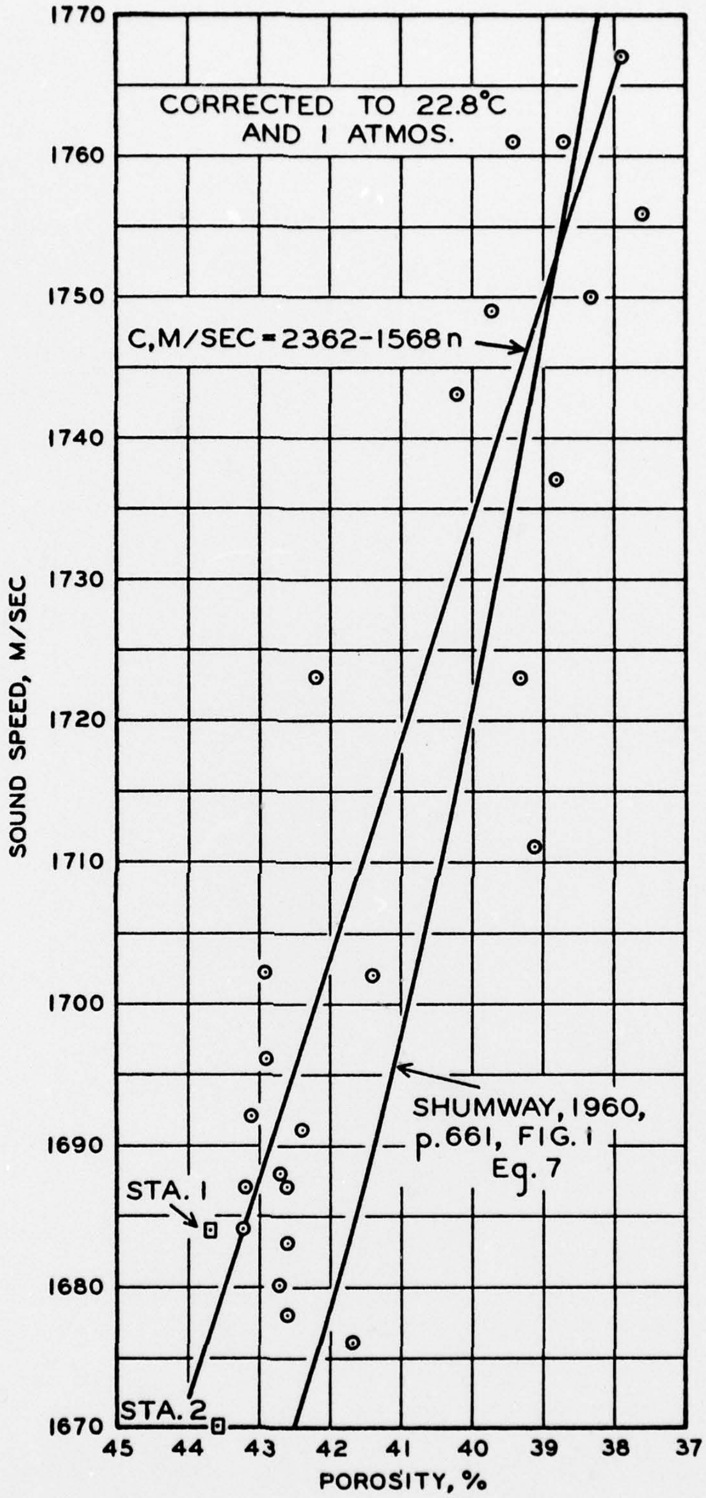

Figure 4. Sound speed vs porosity for some shallow-water sands off San Diego. Straight line relationship is tentative pending more study (see text); fine and medium sands between the porosity and sound-speed ranges shown are only values considered.